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evidence for stoping in this magma chamber, but the well-exposed features of the inclusions of this granite are opposed to this mechanism of intrusion.

FOLIATION IN THE GRANITE

Both Runner and Paige recognize a certain amount of assimilation. While Runner considers its effect appreciable, Paige[1] points

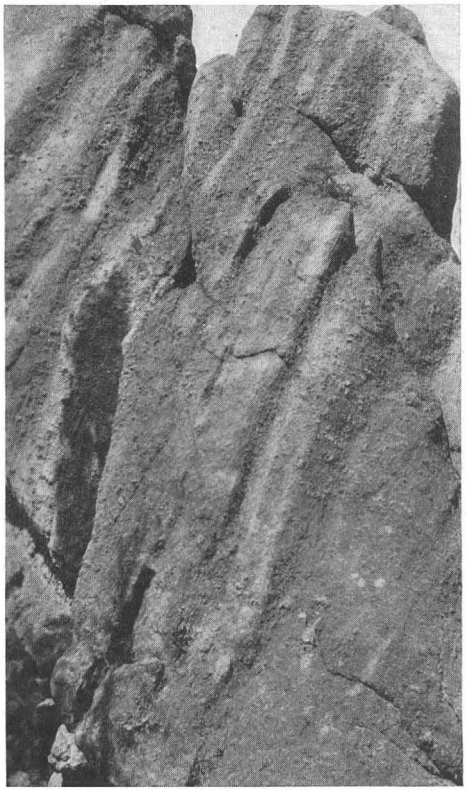

FIG. 11.—Detail view of Figure 10

out that the *mechanical* disruption of the schistose wall rocks by the granite down to a small scale may ultimately result in such an intimate mixture of both rocks that the following chemical attack is insignificant as compared with the preceding mechanical shredding of the sediments. To this the writer would add that the visible features of such mechanically comminuted wall rocks may be almost

[1] *Op. cit.*

indistinguishable from assimilation phenomena. How, then, can we determine the relative importance of assimilation?

It can hardly be overemphasized that the parallel orientation of micaceous minerals in igneous rocks is not, in itself, sufficient evidence of magmatic assimilation. For flaky or discoid crystals, like mica, which are floating for some time in moving liquids will, for hydrodynamical reasons, orient themselves subparallel to the nearest relatively stationary wall along which the magma is moving.[1] If such a wall rock is a schist, and a plane of schistosity forms the local friction-exerting surface—a very common case in nature—then the three elements: schistosity of the wall rock, contact plane, and mineral parallelism of the adjacent igneous rock, happen to be parallel to each other. Additional proof is necessary to show that such mineral parallelism is due to assimilation.[2]

[1] This principle, and observations pertaining to it, are well known to every student of intrusive rocks. Of the numerous papers describing such features, only a few may be cited:

J. E. Spurr and G. H. Garrey, "Economic Geology of the Georgetown Quadrangle, Colorado," *U.S. Geol. Surv. Prof. Paper 63* (1908), pp. 59, 90.

F. E. Vaughan, *op. cit.*, p. 368.

F. F. Grout, *op. cit.*

J. E. Spurr, *The Ore Magmas*, Part I (1923), pp. 167–75.

C. H. Smyth, Jr., and A. F. Buddington, "Geology of the Lake Bonaparte Quadrangle," *N.Y. State Mus. Bull. 207–209* (1926), pp. 48–78.

G. Berg, "Granitstöcke und Gneismassive," *Geol. Rundschau*, Vol. IV (1913), pp. 225–28.

L. Milch, "Die primären Strukturen und Texturen der Eruptivgesteine," *Fortschritte d. Miner.*, Vol. II (1912), p. 200.

F. Rinne, "Geothermische Metamorphose und Dislokation der deutschen Kalisalzlagerstätten," *ibid.*, Vol. VI (1920), pp. 101–36.

H. Cloos, *Einführung in die tektonische Behandlung magmatischer Erscheinungen I: Das Riesengebirge in Schlesien* (1925), pp. 27–32, 51–56.

W. Riedel, "Das Aufquellen geologischer Schmelzmassen als plastischer Formänderungsvorgang, "*Neues Jahrb. f. Min.* Beil.-Bd. LXII, Abt. B (1929), pp. 151–70.

E. Seidl, *Bruch- und Fliessformen der technischen Mechanik*, Part II (1930). This author speaks of "flow stratification" (*Fliesschichtung*) and "structural stratification" (*Gefügeschichtung*) in rolled steel, and illustrates the feature (Fig. III, 2, on p. 3; Fig. V, 1, on p. 5). Professor E. C. Bingham (Department of Chemistry, Lafayette College, Easton, Pennsylvania) informed the writer in a letter recently that the same principle is made use of in the manufacture of artificial mother-of-pearl.

[2] The few xenoliths of lime silicate rock and marble which are scattered through the Harney Peak granite invite a careful investigation which may possibly decide how far the granite has been contaminated by inclusions.

Test cases for the origin of the mineral parallelism are such exposures in which contact planes of the igneous rock cut across the schistosity planes of the surrounding rock. In all such cases which have come to the writer's attention it was found that the mica crystals disregard the mineral parallelism of the surrounding rocks and that they orient themselves persistently parallel to the local contact plane, no matter whether this plane cuts the structures of the wall rocks or not. The Figures 5–9 illustrate this. Granite dikes, in-

FIG. 12.—Sharp cross-cutting contact between schist inclusion and Harney Peak granite (to the right). Southeast spur of Harney Peak, 2 miles east of the Needles.

truded into slightly older granite masses in which an older set of foliation planes is already developed, cut these older flow planes; and the mica flakes within the cross-cutting dike are parallel to the contact plane of the dike (Figs. 5–7). Dikes with internal contact-parallelism cut the schistosity of inclusions at high angles (Fig. 8). Thin layers of mica curve around a projecting edge of a xenolith (Fig. 9).

Particularly instructive is the belt of granite north and northwest of Sylvan Lake. Here the foliation planes dip at 60°–70° to the south or southwest, and mica flakes within pegmatitic schlieren show the same orientation (Figs. 10–11). Schist inclusions, however, which outcrop along this zone, everywhere maintain the characteristic gentle dip (Fig. 8).

In Figure 4 dip angles of foliated granite are compared with a number of observed dips in the schist. The broad expansion of the right-hand area below dip angles of 35° reflects the parallelism in steeply dipping granite dikes which break through the cupola and xenoliths of schist with their gentle dip angles, and which disregard the mineral parallelism in the flat-lying schist.

That the Harney Peak granite has not assimilated its wall rocks appreciably is further demonstrated by the fact that the contact planes of almost all inclusions are sharp and clean-cut (Fig. 12). Elusive, gradational contact zones seem to be quite exceptional features, as far as the writer's experience goes.

Thus, the local foliation of the granite is not, per se, proof of magmatic assimilation. All test cases show the mineral parallelism to be the result, and the expression of, magma flowage along relatively stationary walls. Unless additional evidence can be produced, the effect of assimilation of the wall rocks by the Harney Peak granite must be regarded as very subordinate. It seems highly improbable that the magma chamber has been widened by this mode of magmatic attack, and the writer's field observations corroborate Paige's statement that "the granite of the Black Hills came into its present position in the main by distention of the older rock body under great pressure."[1]

[1] The scarcity of assimilation phenomena in the Harney Peak area is of special interest in view of the fact that the magma has been excessively rich in pegmatitic emanations. The locally very coarse-grained, tourmaline-bearing rock is justly called a pegmatitic granite by Paige. As it is often maintained that igneous emanations are the chief agency of assimilation, it must be borne in mind that there are also exceptions to this rule (e.g., low temperature, as assumed by Paige) and that each plutonic mass may have its individual peculiarities which necessitate and invite detailed studies of the local geological factors.

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ROBERT BALK

INCLUSIONS AND FOLIATION OF THE HARNEY PEAK GRANITE, BLACK HILLS, SOUTH DAKOTA

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ABSTRACT

Sidney Paige's contention that the granite has made room for itself by distension of the crust, and not by stoping and assimilation, is corroborated by a study of the inclusions and the foliation of the igneous rock.

MECHANICS OF INTRUSION OF THE GRANITE

In summarizing the mechanics of intrusion of the Harney Peak granite in the Black Hills, Sidney Paige[1] concludes that the magma has made room for itself by mechanical distension of the wall rocks, and that both assimilation and stoping have played an inferior rôle. In a short abstract, J. J. Runner[2] arrives at about the same results as Paige, but he is inclined to attribute more importance to assimilation than Paige does.

In 1930 the present writer had occasion to spend some sixteen days in the region, and, thanks to the courtesy of Dr. Runner, he was able to visit also some of the more distant mineral localities in the periphery of the granite mass and to discuss many questions with him in the field. It is a great pleasure to acknowledge Dr. Runner's kindness and helpful advice in the field.

In the following pages a few observations are described which may serve to discriminate further between the relative importance of mechanical distension, stoping, and assimilation of the wall rocks by the Harney Peak granite.

LOCAL GEOLOGY

The Harney Peak granite, as is well known, outcrops in the southern portion of the belt of pre-Cambrian slates and quartzose schists which form the core of the Black Hills uplift. The granite outcrops in a round area, about 10 miles in diameter, and is overlain uncon-

[1] S. Paige, "Central Black Hills," *U.S. Geol. Surv. Folio No. 219* (1925), pp. 4–5.

[2] J. J. Runner, "Intrusion Mechanics of the Harney Peak Batholithic Granite," *G. S. Amer. Bull.*, Vol. XXXIX (1928), p. 186.

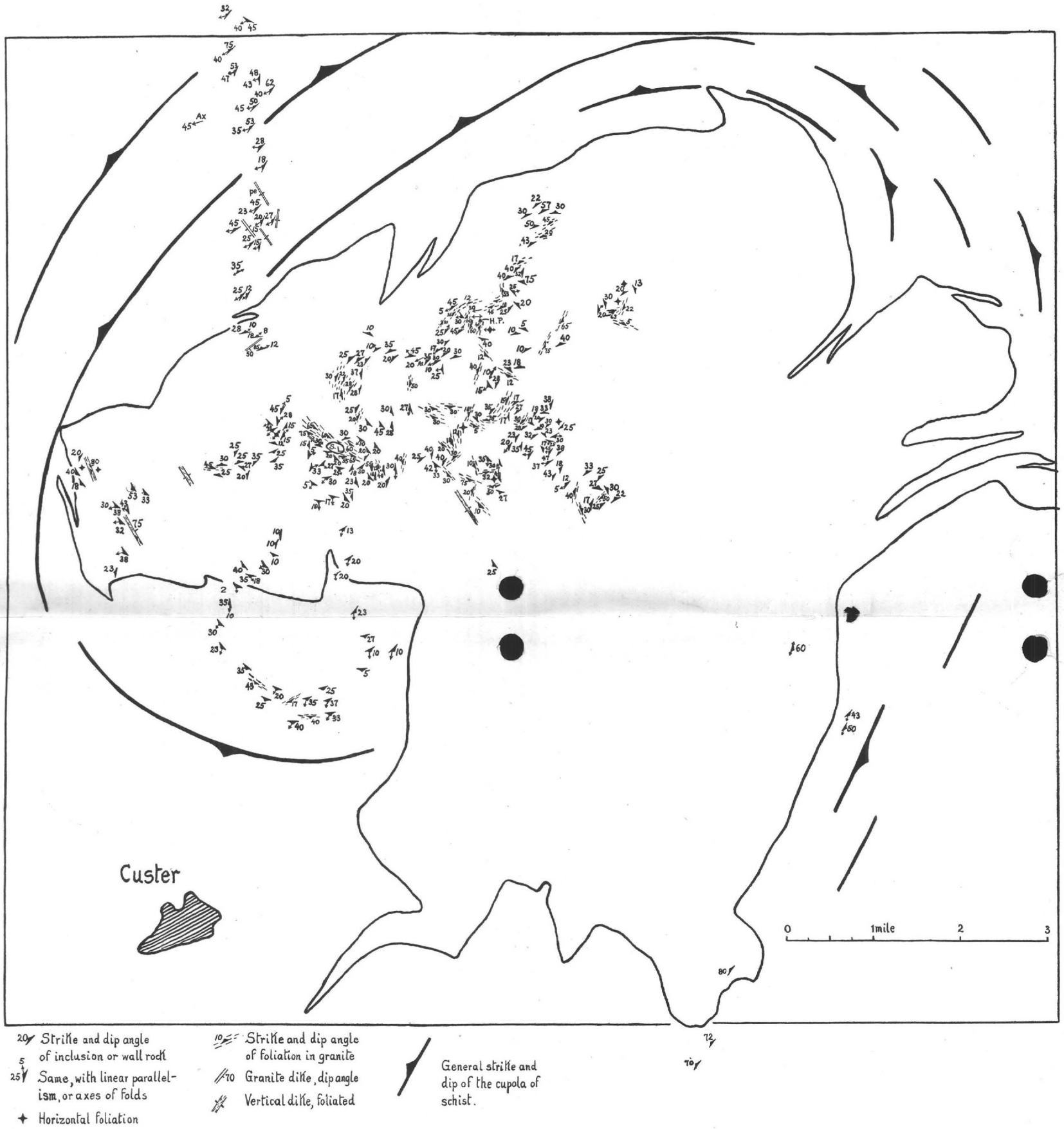

FIG. 1.—Structure map of the Harney Peak granite area, Black Hills, South Dakota. The continuous black line represents the granite contact as shown on the geologic map, Folio 219, U.S. Geological Survey. The granite within this area is not pure, but forms an intricate system of concordant and discordant offshoots, dikes, and lenses. The intrusive is surrounded by a cupola of pre-Cambrian sediments, and hundreds of inclusions within the granite continue and conform to the cupola structure. (*S.L.* = Sylvan Lake; *H.P.* = Harney Peak.)

formably on the east and southeast side by the Cambrian Deadwood formation.

The slates and quartzose schists are strongly folded. The steeply tilted limbs dip to the east or east-northeast; and cleavage, where developed, follows the axial planes for the most part. But when approaching the Harney Peak granite, this regional dip and strike is lost completely in a perfect cupola in the core of which the granite outcrops (Figs. 1 and 2).

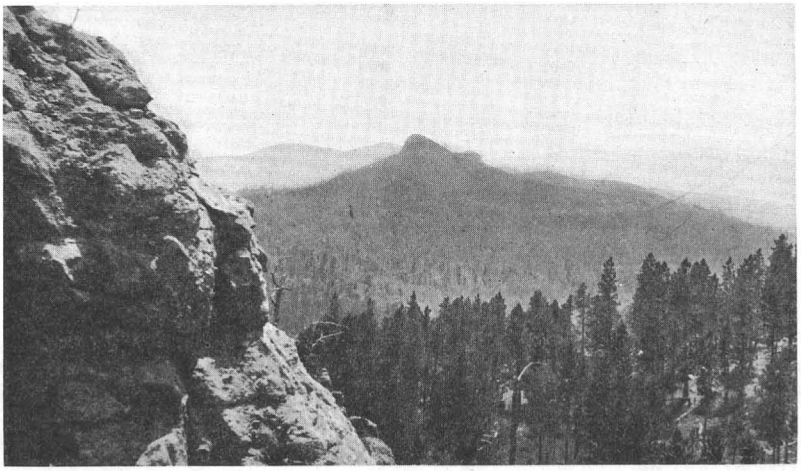

FIG. 2.—The cupola structure of the pre-Cambrian slates in the contact zone of the Harney Peak granite causes gentle dip slopes away from the granite core and steep escarpments facing the central peak. Looking southwest along the west flank of the granite. The top of the hill is a small sill-like granite lens, dipping with the foliation of the phyllite to the northwest. The base of the mountain is composed of the same sediments, dipping in the same direction.

Paige[1] explains this change in structure about as follows: The granite has compressed the crust so strongly from below that the previously folded sediments finally yielded to this force; and the beds, no matter what their previous strike and dip, were contorted and subsequently blotted out into the dome structure which so conspicuously encompasses the intrusive rock. The granite is sufficiently viscous to supply at once pressure and support from below. In the center of the area, the granite expanded so much that the coherence

[1] *Op. cit.*, p. 5.

of the cupola-shaped cover of sediments was severed. The rocks were disrupted, and the individual fragments have been floating on top of the granite core.

FEATURES OF THE INCLUSIONS

Paige[1] calls attention to the fact that close recumbent folds occur in the cupola of schist. The writer cannot but confirm this observation, and would add that isoclinal folds are also found in schist inclusions within the main mass of the granite. Since it is difficult, in general, to demonstrate genetic relations between magmatic intrusions and folding of the surrounding sedimentary rocks, the Harney Peak area is of especial interest, as it shows that a moving mass of magma is, indeed, capable of producing folds independent of the structure of the same rock farther away from the igneous rock. In the area under discussion, the limbs of these secondary folds slope away from the granite core, constituting the now visible cupola. Unfortunately, not sufficient data are available to determine how the axes of these secondary folds are arranged. Wegmann[2] postulates that the axes of folds should be more or less vertical along the periphery of rising mobile masses, and that all other linear structures, such as flow lines, or stretching of sedimentary wall rocks, should arrange themselves in the same way. This is actually found in salt domes[3] and in certain volcanic plugs,[4] and also along the contacts of such intrusives as moved upward faster than sidewards, e.g., in certain parts of the Sierra Nevada granodiorite.[5] But it must be remembered that the same linear structures will not conform to the direction of

[1] *Ibid.*

[2] C. E. Wegmann, "Über Diapirismus (besonders im Grundgebirge)," *Comm. Geol. de Finlande Bull. 92* (1930), pp. 58–76, especially p. 67.

[3] F. D. Vaughan, "The Five Islands, Louisiana," in *Geology of Salt Dome Oil Fields* (Amer. Assoc. Petrol. Geol. symposium, 1926), pp. 366, 368; K. Stier, "Strukturbild des Benther Salzgebirges," *Achter Jahresbericht d. Niedersächsischen geologischen Vereins zu Hannover* (Hannover, 1915).

[4] F. D. Adams, "The Monteregian Hills," *Jour. Geol.*, Vol. XI (1903), pp. 239–82, especially p. 279; F. F. Grout, "Internal Structures of Igneous Rocks, etc.," *ibid.*, XXVI (1918), pp. 439–58, with Bibliography; H. and E. Cloos, "Die Quellkuppe des Drachenfels am Rhein," *Z. f. Vulkanologie*, XI (1927), pp. 33–40.

[5] H. Cloos, *Bau und Bewegungen der Gebirge in Nordamerika, Skandinavien und Mitteleuropa* (Berlin: Gebr. Borntraeger, 1928), p. 250.

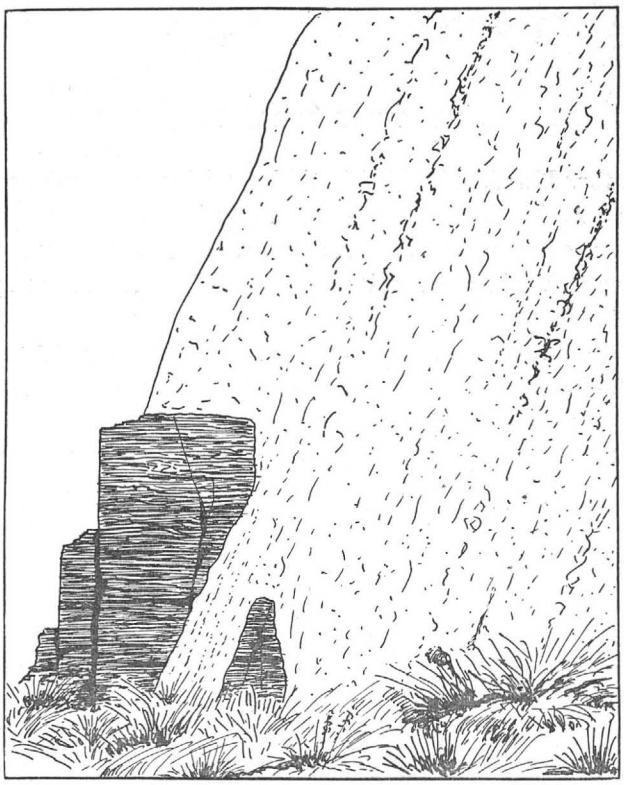

FIG. 8.—Cliff of granite, ⅓ mile northwest of Sylvan Lake, showing flat-lying schist inclusions, split apart by a granite dike. Foliation in the dike and in the surrounding granite wall dips steeply to the southwest, irrespective of the attitude of the xenolith.

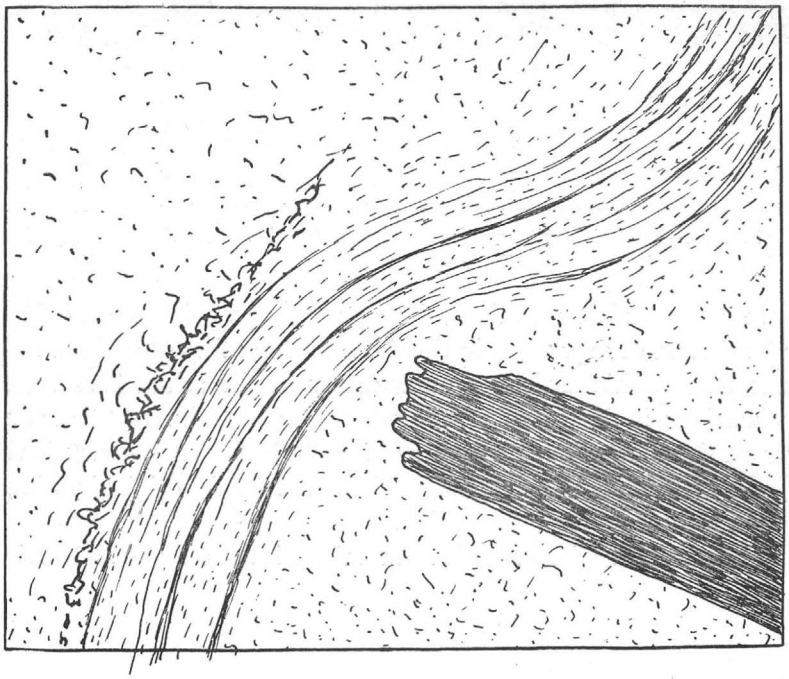

FIG. 9.—Local schlieren of mica in granite at right angles to the foliation of an adjacent schist inclusion. One mile west of Sylvan Lake. Six by five feet.

tated water. If suddenly fixed in their position, each cake would be found in a subhorizontal position, but dipping in random directions. It may be, of course, that in some parts of the Harney Peak area which the writer has not visited, such gentle anticlines or synclines

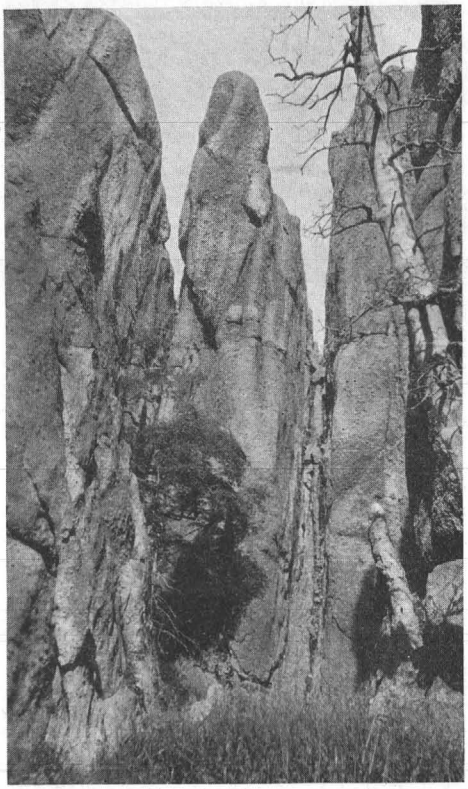

FIG. 10.—Cliff of granite, northwest of Sylvan Lake. Note the steep dip of the foliation and of pegmatite schlieren.

are suggested; but even then, these structures would be due only to a local crest or depression in the dome surface; they would not indicate pre-granitic anticlines or synclines of the schist because, as pointed out in the foregoing, the now flat-lying schist fragments represent the blotted-out remnants of isoclinal folds. In no case is the gentle attitude of the inclusions to be taken for the original position of the sediments after deposition.

Thus, as far as the writer is aware, there is not only no supporting

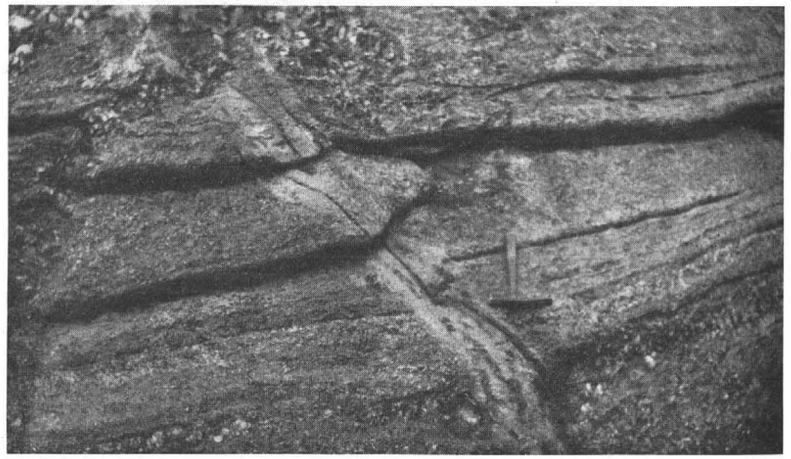

FIG. 5

FIG. 6

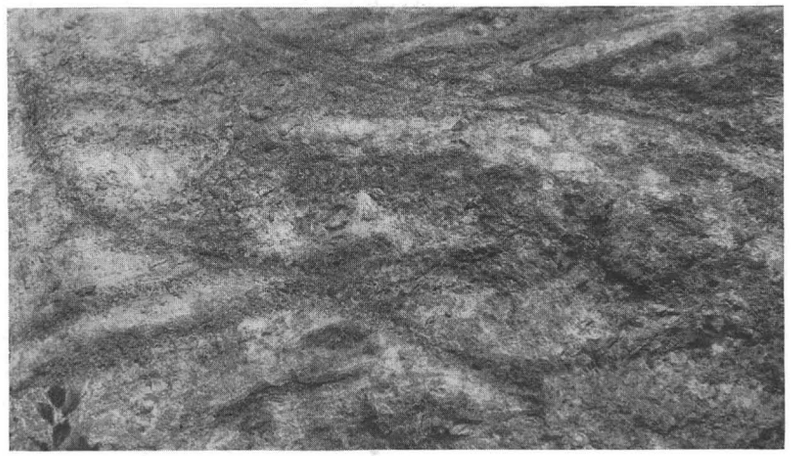

FIG. 7

FIGS. 5, 6, AND 7.—Foliated granite is traversed discordantly by dikes of foliated granite. The flow planes in the dikes are parallel to the contact walls, and cut the foliation of the wall rock at high angles. Figures 4 and 5 near top of Harney Peak; Figure 6 on west spur of the peak, ½ mile east of Sylvan Lake.

steepest ascent as soon as the mass expands in any other direction faster than upward. If, for instance, a rising dome on its journey upward should temporarily expand faster in a lateral direction, by advancing, say, into a fissure system of appreciable room capacity, or by spreading along a flat-lying zone of structural weakness, the linear elements will arrange themselves in those directions in which the material is being deflected. In this manner a very flat arch of the flow lines may ensue which does not record directly the upward motion, although the apex of such an arch does indicate the tendency of the mass to rise.

The writer has, unfortunately, only twenty-three reliable measurements of the strike and pitch of axes on hand, taken partly from the belt of schist which surrounds the granite, partly from inclusions within the granite. The projected strike shows a broad maximum in east-west to southwest-northeast, while the gentle pitch is uniformly to the west or southwest. The western half of the granite area has been examined more carefully than the eastern portion. To judge from these few data, the granite seems to have expanded laterally more readily than upward; but more measurements are necessary to decide this point definitely.

Obviously, rocks must attain a high degree of plasticity before the structure of pre-existing folds can be obliterated and a new system of isoclinal folds be imposed on the material. The mechanics whereby such transformation of structures of different ages and in different directions takes place has been studied by A. Heim,[1] Behre,[2] W. Schmidt,[3] Born,[4] B. and R. Willis,[5] Sander[6] and Scholtz;[7] and

[1] Alb. Heim, *Geologie der Schweiz*, Vol. II (1921), pp. 81–83, plate II, and p. 78.

[2] C. H. Behre, Jr., "Observations on Structures in the Slates of Northampton County, Pennsylvania," *Jour. Geol.*, Vol. XXXIV (1926), pp. 501, 502; "Slate in Northampton County, Pennsylvania," *Pa. Geol. Surv.*, 4th Series, *Bull. M9* (1927).

[3] W. Schmidt, "Gesteinsumformung," *Denkschriften d. Naturhist. Museums zu Wien*, Vol. III (1925).

[4] A. Born, "Gefügestudien an Gesteinen des varistischen Gebirges," *Neues Jahrb. f. Miner.*, Beil.-Bd. LII, Abt. B (1925); "Über Druckschieferung im varistischen Gebirgskörper, "*Fortschritte d. Geol. und Paläont*, Vol. VII, Heft 22 (1929).

[5] B. and R. Willis, *Geologic Structures* (1929), pp. 189–92.

[6] B. Sander, *Gefügekunde der Gesteine* (1930), pp. 33–53, 221, 247, 252, 253.

[7] H. Scholtz, "Das varistische Bewegungsbild," *Fortschritte d. Geol. und Paläont.*, Vol. VIII, Heft 25 (1930), pp. 241–54, plates I, II.

E. B. Knopf[1] has recently given an admirably clear résumé of these and related problems. It is in the nature of secondary adjustment movements that folds, and especially apexes of folds, become scarcer and more appressed, because the micaceous layers adjust themselves to the changing directions of compressive and rotational strain by glide movements along suitably oriented shear planes rather than by folding (Fig. 3).

FIG. 3.—Typical view of a schist inclusion in the Harney Peak granite. The layers of schist are horizontal or dip gently in random directions; they are often isoclinally folded or crumpled. Southeast spur of Harney Peak, 2 miles from the summit.

Although, in the writer's opinion, the formation of the cupola is satisfactory proof of the powerful expansion and deforming action of the present intrusive; and although it appears highly improbable that a large mass of magma would, for no conceivable reason, change its mechanism of movement during a penultimate stage of its advance, it might be argued, nevertheless, that the magma, after attaining its present site in the earth's crust, has further widened its chamber by stoping. It may be assumed that between the arrival of the granite at its present location and its final consolidation there was an intervening period during which the magma chamber, filled with a stationary liquid, grew in height by the

[1] E. B. Knopf, "Retrogressive Metamorphism and Phyllonitization, Part I," *Amer. Jour. Sci.*, Vol. XXI (1931), pp. 1–27.

downward slumping of severed blocks of the roof, while the granite took possession of the space formerly occupied by these blocks. In this case it is reasonable to assume also that the xenoliths would be assimilated by the surrounding granite the deeper down they moved.

It may be repeated that neither Paige nor Runner entertains this theory, but they do not seem to have stated in sufficient detail why these assumptions must be discarded.

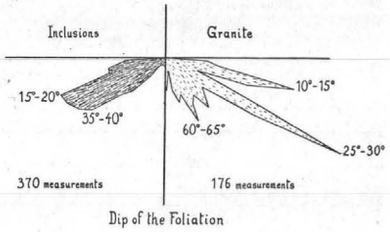

FIG. 4.—Statistical diagram of the dip angles of inclusions (left-hand side) and foliation of the Harney Peak granite (right-hand side). Distances from center indicate relative number of measurements. The schist inclusions dip uniformly at low angles from 15° to 35°; whereas steeper dip angles are observed in the foliated phases of the granite, especially where steep dikes cut across gently dipping inclusions.

The great majority of the inclusions are slabs parallel with the planes of schistosity. Now floating discoid bodies tend to arrange their longest axes subparallel with the direction of swiftest movement. If such platy xenoliths were floating downward, it must be expected that a majority of them show steep dip angles. But Runner emphasizes the *gentle dip* of most inclusions. The accompanying map shows the orientation of several hundred of them, and Figure 4 indicates the maximum dip to be between 15° and 35°, in best agreement with Runner's statement.

Because of the gentle dip angles, it cannot be assumed that the exposed xenoliths have floated downward; instead, the individual fragments have moved in subhorizontal directions. Since these planes of movements grade marginally into the cupola of the wall rock, it must be the excessive distension and expansion of the central portion of the cupola which has led to their present position.

Runner adds: "Plotting dips and strikes of inclusions reveals gentle folds."[1] During his limited visit to the region, the writer has been unable to find such features. In the central spurs of Harney Peak, which represent the structural apex of the dome, adjacent xenoliths do show gentle dips, but they strike at random. The picture resembles somewhat that of cakes of ice on the surface of agi-

[1] *Op. cit.*